Screen printed temporary tattoos for skin-mounted electronics

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Screen Printed Temporary Tattoos for Skin-Mounted Electronics

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***Abstract*—This paper focus on fabrication and analyzation of screen-printed temporary transfer electrical tattoos. Stretchable conductive traces and insulator layers are printed on a transfer tattoo paper. The screen-printed structures are electromechanically analyzed. Four different test structures were used to evaluate the sheet resistance and the quality of the printing process. The sheet resistance of the samples are 41 ± 6 mΩ/□. The breaking point for the tensile test was 19 %. Finally, on-skin performance was evaluated by attaching a printed tattoo on a knee and backhand of a test person. The skin-mounted tattoo showed good electrical performance and conformability.**

Keywords-stretchable electronics, temporary electrical tattoo, printed electronics

I. Introduction

Current wearable electronics is mainly based on rigid circuit boards. The circuit board defines the size, shape, and form factor of the unit, leading typically to bulky and clumsy wearable systems. Miniaturization of electronics has improved the user comfort, however, to reach the full potential of wearables, electronics hardware must become soft, light-weight, thin, conformable to the body and, especially, inexpensive to manufacture. Therefore, the electronics must be stretchable and mass-producible.

The development of functional inks has enabled the use of printing methods to manufacture electronics. So far electronics is mainly fabricated using substractive methods such as photolithography. Printed electronics, however, is an additive manufacturing method. Additive means that a small amount of functional ink is applied directly and accurately on a substrate, for example, by inkjet, screen, offset, or gravure printing technologies. The solution can contain functional materials such as metal flakes, oxides, polymer conductors, or semiconductive materials. Furthermore, recent development with silver nanowire [1], carbon nanotube (CNT) [2], and graphene inks [3], have enabled stretchable interconnections [4], sensor elements [5, 6], and circuits [7, 8].

Skin-mounted e-patch is an ideal form factor for remote monitoring of health metrics, and therefore, academics and industry have shown growing interest towards these technologies in recent years. Technology solutions have evolved from thick bandage-like structures currently on market to novel ultra-thin, soft, and transparent tattoo-like films. When mounting electronics on top of the skin, things like stretchability and conformability must be considered. In some places, human skin can stretch even more than 30 % [9]. However, in many wearable and skin-mounted applications it can be less [10]. This sets the strain target for skin mounted electronics. High conformability can be achieved with ultra-thin layers [11]. L. Wang et al. investigates the relationship between a membrane thickness and conformability [12]. Ameri et al. demonstrated that 510 nm and thinner films of PMMA conforms on a human skin [13]. This thickness is an extreme requirement for complete stack, which is hard to achieve together with a low resistance conductive elements requirement in wireless communication system. However, the situation is not as straight forward, and several parameters are determining the conformability of the system as presented in [12]. As an example, the maximum film thickness for fully conformable films depends from the film and membrane material.

The earliest electrical tattoo-like work was reported by Dae-Hyeong Kim et al. [14]. They also introduced a new term “epidermal electronics” to refer electronics that is like an epidermal layer of a human skin. This means that electronics should have skin like properties in terms of thickness, mechanical behavior (i.e. elastic modulus, bending), and density. Later Woon-Hong Yeo et al. [11] demonstrated a fabrication method and an electrical device based on poly(vinyl alcohol)(PVA) template that was used to transfer an electrical circuit on a skin.

Casson et al. [15] proposed inkjet printing of electrodes on to a transfer tattoo paper. This enabled transferring the electrodes on the skin by wetting the paper. However, they needed an adhesive sheet with a thickness of 10 µm to improve the adhesion between the skin and the electrodes. Ameri et al. [13] reported ultra-thin and transparent electrical tattoos based on the graphene. They proposed so thin structure that it conformed on a skin, and therefore, they did not need an additional adhesive. However, the sheet resistance of the device was relatively high, which might be suitable for some applications like electrodes and sensors. However, much lower sheet resistance values are needed for high-frequency components like antennas.

This contribution presents a screen printed conductive and dielectric films on a temporary transfer tattoo template. The fabricated films are electromechanically characterized.

II. Materials and Methods

A. Materials

Substrate material in this research was temporary transfer tattoo paper from Silhouette [16]. Thermal properties of this particular paper was not available. Sanchez-Romaguera et al. investigated the heat stability of another tattoo paper using thermogravimetric analysis (TGA) [17]. According to their findings, the processing temperature should not exceed 135 °C. A baking test was done in order to estimate maximum annealing temperature of the paper. The pieces of the transfer tattoo paper were baked in oven at 100 °C, 120 °C, 140 °C, and 160 °C for 20 min. The paper did not show any visible color change with 100 °C and 120 °C. Minor and remarkable color changes were identified in samples annealed at 140 °C and 160 °C, respectively. Based on the work of others and these results, it was concluded that maximum annealing temperature for this tattoo paper is 20 min at 120 °C.

For conductive traces, a commercially available conductive silver-flake ink was used (CI-1036 by EMS) [18]. This ink is screen printable and stretchable. It has high conductivity, but it is not transparent. Furthermore, the estimated film thickness is higher than 10 µm, which may restrict the conformability with the skin. Despite of these limitations, this ink was selected due to the low processing temperature (120 °C) suitable for the selected substrate. Furthermore, the ink has high stertchability and conductivity suitable for RF antennas.

For cover layers, a UV-curable screen printable DI-7540 (from EMS) was selected [19]. This ink is stretchable and designed to function with the CI-1036 ink. The recommended film thickness when printed on top of the silver conductor is 36 µm in order to avoid pinholes [19]. The cover layer will increase the total thickness of the stack (temporary tattoo, conductive film, and dielectric film) and might decreases the conformability of the electrical tattoos.

B. Fabrication

Printing was done by using a TIC SCF-300 semi-automatic screen-printing machine. A polyester mesh screen was used in the printer. The mesh was attached to a $500 \times 3000\ mm^2$ aluminum frame with a profile of $30 \times 30\ mm^2$. The mesh count was 79 threads/cm, the thread diameter was 55 µm, and the mesh opening was 69 µm. The stretching angle of the mesh was 22.5°.

The screen printer was prepared according to instructions, and the conductive layers were printed first. After setting pressure values, snap-off, and alignment of squeegees, the conductive patterns were printed, dried, and annealed according to instructions (II. A.). Cover layer was printed on top of conductors after sheet resistance measurement. The cover layer was annealed according to manufacturer instructions.

C. Characterization

Four different geometries were designed and fabricated for electrical and electromechanical characterization as shown in Fig 1. These structures are named: i) Greek cross (GC), ii) bridge resistor (π), iii) big squares (BS), and iv) U-shape. The width of the lines is 1.0 mm and the size of the pads are approx. 9.0 mm^2. The length of the bridge resistor (π) under the test is 10 mm. The size of BS pattern is 900 mm^2. The U-shape pattern is previously used on strethcable electronics characterization. The total length of the U-shape pattern is 188.4 mm [10].

The sheet resistance of GC, π, and BS were determined using four point method that consists of a probe station and Keithley 2425 Sourcemeter. Sheet resistance of U-shape is determined using 2-point measurement setup. Each test card contained 6 GC, 6 π, 4 BS, and 5 U-shape patterns. Four test card were fabricated. The total number of test samples are listed in Table I.

TABLE I. Number of Samples

	GC	π	BS	U	
Set 1	6	6	4	5	21
Set 2	6	6	4	5	21
Set 3	6	6	4	5	21
Set 4	6	6	4	5	21
	24	24	16	20	

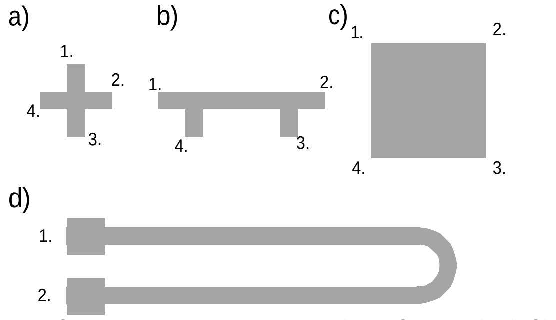

Figure 1. Sheet resistance test structures: a) Greek cross (GC), b) bridge resistor (π), c) big squares (BS), and d) U-shape.

Electromechanical characterization were performed by integrating a tensile test and a sourcemeter. Tensile tests were done with U-shape pattern and 2-probe method. Previously used Keithley 2425 Sourcemeter were combined with a LabView program via GPIB interface to store the data. Tensile tests were done with both an Instron 4411 and on-skin measurement setups.

The challenge with electromechanical characterization is that the printed temporary tattoo structure cannot be electromechanically characterized if not transferred onto a template or carrier. Thermoplastic polyurethane (TPU) is commonly used substrate material for printed stretchable electronics. We selected Epurex Platilon U4201 to act as a carrier material during the tests. The data logging frequency was set to 5 Hz.

In on-skin resistance measurement, the U-shape pattern was attached on a knee of a test person.

III. Results and Disscussion

A. *Sheet resistance measurement*

Sheet resistance of thin film can be determined with different structures. In this work, different test methods and their suitability for computing sheet resistance are analyzed. At the beginning, the sheet resistance of GC structures were determined by measuring the sheet resistance from two positions. The results are shown in Fig. 2. As seen from the Fig., the average sheet resistance values between the Set 1-3 are almost identical, but the Set 4 showed clearly a higher sheet resistance value as well as a wider confidence interval (95 % CI) indicating also a larger variance. This means that Set 1-3 have quite uniform printing quality in both direction in x-y plane and between each other.

After this, the sheet resistance of different geometries were computed in order to determine the quality between different resistance patterns. Fig. 3. shows the sheet resistances of the GS, BS, π, and U-pattern in each set. The average between the samples as well as the variance are quite similar between the samples. However, the sheet resistance of Set 4 is clearly higher compared to Set 1-3 as already noted. In addition, the Set 2 BS pattern seemed to have higher resistance compared to other patterns inside the Set 2. The higher resistance of Set 2 BS is most likely due to fabrication deviation inside the test card while the higher resistance in Set 4 is most likely due to process variance between the test cards. Potential explanation is the drying of the ink on the screen, which will partially block the holes of the screen, and therefore less material is transferred on the substrate. This emphasizes the need of screen maintenance during the fabrication process. The average sheet resistance of samples, excluding the resistances of Set 2 BS and Set 4, was 41 ± 6 mΩ/☐. The sheet resistance values of Set 2 BS and Set 4 are more than two standard deviation higher than the average of other samples as seen from Fig 2. These numbers verifies the above statement about problems in ink transfer. Furthermore, the obtained sheet resistance values are comparable with the results achieved with same ink printed on a TPU (36 ± 5 mΩ/☐) substrate [10].

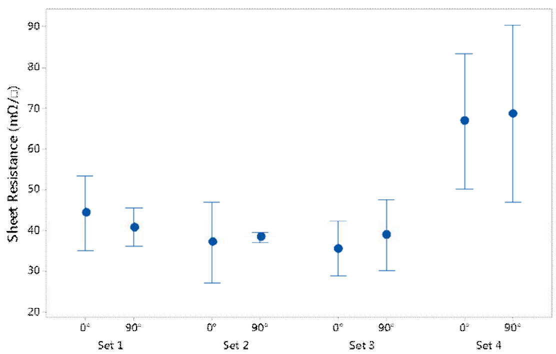

Figure 2. GC sheet resistance values of Set 1-4 in measured in 0° and 90°.

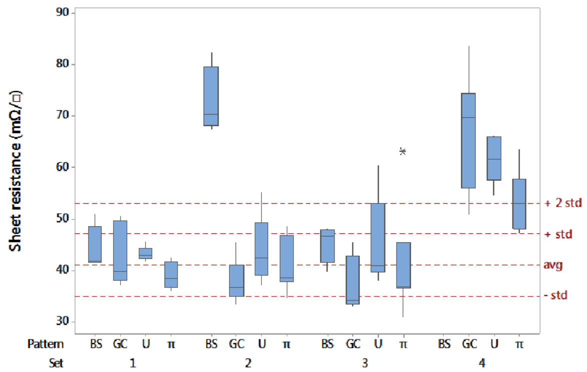

Figure 3. Sheet resistances of the BS, GC, U, and π patterns including average and standard deviations.

B. *Influence of the cover layer*

In order to analyze the impact of the insulator layer, a dielectric cover layer was printed on top the Set 1 and Set 2 conductors, and cured with UV. Fig. 4. shows the histogram of the sheet resistance of non-covered and covered samples. It can be seen that printing and annealing of the cover layer

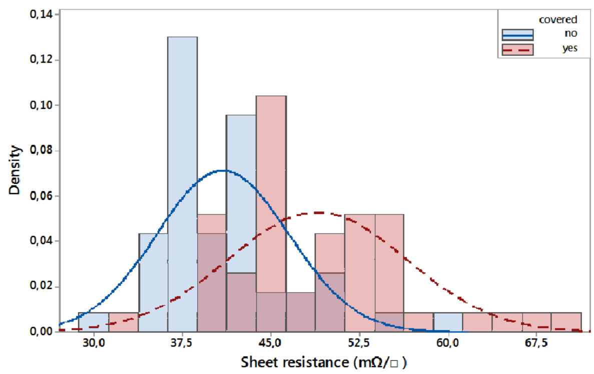

Figure 4. Sheet resistances of non-covered samples as a function of covered samples from Set 1 and Set 2.

increases the resistance and standard deviation of the sheet resistance. The average sheet resistance and standard deviation of non-covered and covered samples are 41 ± 6 mΩ/☐ and 49 ± 8 mΩ/☐, respectively. This equals an increase of 17 %, which is relatively large. Despite this increase, the sheet resistance is still on a relative low level compared to the results reported for graphene [3], CNT [2] and Ag-nanowires [1] as listed in Table II. This means that printed transfer tattoo could be used in wireless applications like antennas for RFID, WLAN or Bluetooth.

TABLE II. SHEET RESISTANCE OF DIFFERENT MATERIALS IN TEMPORARY TATTOO APPLICATIONS

Ink	Sheet resistance (Ω/□)	Ref
AgNW	50-100	[1]
CNT	20-700	[2]
Graphene	30 -100 k	[3]
Ag-flake	0.05	[this work]

C. *Electromechanical performance*

The electromechanical characterization was performed using Instron 4411 tensile strength tester as described earlier using U-shape pattern that were covered with insulator ink. Fig. 5. presents a resistance as a function of strain. The y-axis is normalized to initial resistance (R/R_0).

From Fig. 5. it can be seen that there is large fluctuation and sudden spikes in the resistance value at the beginning and at the end of the test. An exponential increase of the resistance and the fluctuation of the resistance at the end is expected due to the disconnection and fracture in a conductive path. Similar results are reported earlier in [10]. Furthermore, Fig. 5. shows some unexpected and undesirable fluctuation of the resistance at the beginning of the test. The resistance rapidly increased 50-100 times on these peaks. These spikes can be caused by the measurement setup itself, which is not ideal for transfer tattoo characterization. The general problem is that electrical tattoos are so thin that they need to mounted on a separate carrier / template in order to perform electromechanical tests. This will cause variation in strain uniformity of the device under test. In ideal case, the mechanical properties of the carrier and the adhesion between the electrical tattoo and the carrier should be comparable with a human skin. If the mechanics and adhesion differs a lot, it causes uncertainly to the measurement setup since the stretching is actually happening though the carrier and not directly by moving clamps. In our tests, we used TPU carrier, which is not an ideal in order to mimic the human skin. This carrier was selected since it was previously used to analyze the performance of the stretchable ink itself. By selecting the same substrate, we can compare the results of electrical tattoo to directly printed results. This, however, will restricts the analysis only for the breaking point of the conductor.

As seen from the Fig. 5, the resistance starts to increase suddenly around the strain level of 16 %, and the complete failure occurs at the strain of 19 %. This is relatively small value compared to the results achieved by printing the same ink directly on TPU. J. Suikkola et al. received 74% elongation with the same ink printed directly on the TPU [10]. These results demonstrates that substrate material has remarkable impact on electromechanical behavior of the system. Furthermore, the results indicates to limit the use of presented electrical tattoo on body locations were the stretchability is limited to less than 15 %.

D. *On-skin resistance measurements*

Since the strain test with tensile test machine was limited

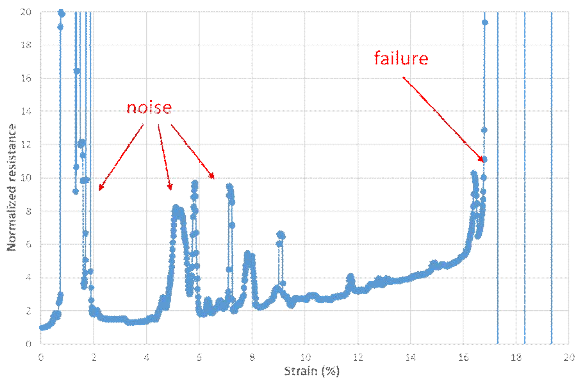

Figure 5. Normalized resistance of U-shape pattern from strain tests.

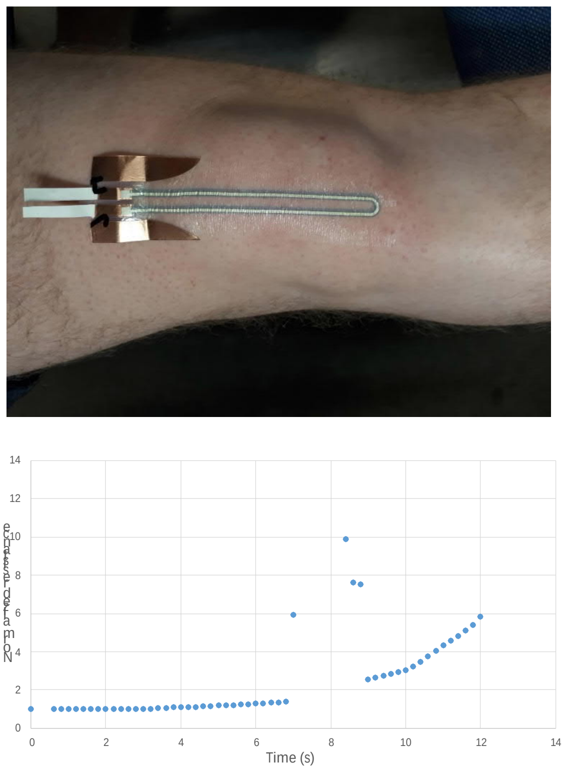

Figure 6. (top) image of an U-shape tattoo mounted on a skin and (bottom) a normalized resistance the test sample as a function of time when knee is bended.

due the fact that electrical tattoo was mounted on TPU carrier, we performed on-skin resistance measurement. On-skin resistance measurement was done by attaching a U-pattern sample on the knee of a test person. This test method has other limitations and difficulties, which limited the number of test samples, and therefore, only couple of samples were successfully measured. Fig. 6 shows the normalized resistance as a function of time when the knee of the test person was bended. Fig. 6. shows much smoother resistance increase with less noise compared to electromechanical tests shown in Fig. 5, especially at the beginning of the test. This supports the previous hypothesis related to the challenges of the test methods and substrate interaction.

In Fig. 6., the normalized resistance increases up to 25 at the eight second mark. However, the conductor cannot be considered broken, since the resistance returns back to the original steady increase until it breaks after 12.4 seconds.

E. Conformability of the screen printed electrical tattoos

Finally, the conformability of the proposed electrical tattoos was observed by transferring a π-shape stack on the back of the hand of a test person. The conformability was visually observed. Fig. 7 shows an example of printed π-shape transfer tattoo on the backhand of a test person. In order to analyze the results in detail, we need to remind that the tattoo has a stack of materials. The silver conductors are printed on a top of a tattoo paper and blue color shows the cover layer insulating the conductor from the skin. The cover layer is not printed on top of the measurement pads. The full stack of the conductor and cover layer seem to conform on the skin at least partially. This can be seen from the bridge resistor location. The thickness of this stack is approx. 40 µm, which is relatively large, and needs additional adhesive film to be mounted on the skin. The stack on top of measurement pads is thinner, approx. 15µm, and therefore, the features of the skin are much clearer on the areas where only the silver is applied.

IV. CONCLUSIONS

In this work, we presented a fabrication of electrical temporary transfer tattoo by screen printing conductive and insulating layers. A sheet resistance of 41 mΩ/□ was achieved. This is relative low value compared to reported values with CNT, AgNW, and graphene. Low sheet resistance is needed for high-frequency applications such as remote healthcare applications.

The elongation at break achieved during the electromechanical tests was 16 %, which is much smaller value compared to values reported by direct printing on 50 µm thick TPU film (74 %). Thus the proposed screen-printed temporary tattoo stack is recommend to use in low strain (10-15%) level applications.

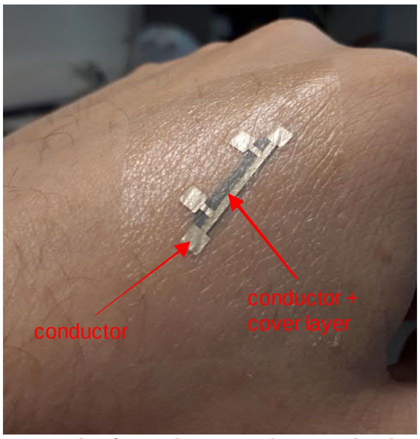

Figure 7. An example of printed tattoo stack mounted on hand.

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